

Enhanced $\pi \cdots \pi$ interactions in α,β -unsaturated carbonyls †

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High level *ab initio* calculations on complexes of benzene with acrolein and ethene reveal that $\pi \cdots \pi$ interactions to electron deficient acrolein are remarkably similar to those found in the benzene dimer.

Attractive interactions between π -systems have been recognised for over 20 years as important factors in the structure of biological systems, crystal packing, and molecular recognition.¹ To date, most experimental and theoretical attention has been focused on the benzene dimer as a model system for $\pi \cdots \pi$ interactions, its small size and high symmetry lending itself to detailed investigation. The consensus view of the benzene dimer is that the symmetrical face–face or parallel orientation is less stable than either T-shaped or slipped-parallel geometries, and that interaction energies are comparable to weak hydrogen bonds in the region of 10–15 kJ mol⁻¹.²

Aromatic systems other than benzene have also been studied extensively. Nitrogen-containing heterocycles such as purine and pyrimidine act as model systems for DNA bases,³ while sulfur and oxygen containing aromatics are important in electronic materials such as tetrathiafulvalene (TTF).⁴ However, studies of non-aromatic systems have largely been limited to systems such as benzene interacting with tetracyanoethene (TCNE), which are perhaps better described as charge-transfer systems rather than purely $\pi \cdots \pi$ interactions, although we note that Oki *et al.* have reported *ab initio* calculations indicating that the face \cdots face interaction is attractive in the benzene \cdots ethene complex.⁵

We have used high-level theoretical techniques to study the $\pi \cdots \pi$ interactions in two models that involve non-aromatic π -systems, namely acrolein and ethene interacting in a ‘face–face’ manner with benzene (see Fig. 1). As well as the

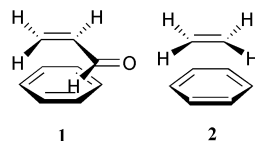


Fig. 1

fundamental interest in how double bonds interact with aromatic rings, we are also interested in the use of such interactions to control the diastereofacial discrimination of unsaturated carbonyl compounds, thereby giving rise to possible stereoselective transformations. There are many examples within the literature that infer face–face $\pi \cdots \pi$ interactions to explain the origins of stereoselectivity in synthetic transformations,⁶ and a more rigorous and fundamental understanding of this fascinating yet little understood non-covalent interaction would help in the future design of chiral catalysts for enantioselective transformations.⁷ Such control may require rather strong interactions, but excessively strong binding could also prevent

subsequent release of product, however, it has recently been shown that it is possible to modulate face–face $\pi \cdots \pi$ interactions by altering the electronics of an η -6 chromium atom appended directly onto the aromatic ring of an 8-phenyl menthol acrylate.⁸ Ultimately, our goal is to be able to modulate the strength of such interactions through substitution or other modification. This will then yield a method for discriminating between the diastereotopic faces of an α,β -unsaturated carbonyl through electronic rather than steric interactions, thus providing catalysts that are non-substrate specific.

Initial starting structures were generated by placing optimised structures of benzene and acrolein (**1**) or ethene (**2**) approximately 3.5 Å apart in a face–face orientation. Optimisation and harmonic frequency calculations at the MP2/6–31G(d) level⁹ using Gaussian 98¹⁰ confirmed that this orientation is a true minimum in both cases. Calculations at the same level (not reported) on other conformations, such as those containing C–H \cdots π or C–H \cdots O hydrogen bonds, indicate that this face–face orientation is also the global minimum for complex **1**. The most stable of these complexes, which forms a C–H \cdots π H-bond through the α -carbon of acrolein, is 4.8 kJ mol⁻¹ less stable than the face–face orientation. This is at odds with the benzene dimer, in which these two orientations have almost identical stabilisation. Despite applying no symmetry constraints, **2** adopts C_{2v} symmetry with the benzene ring and double bond midpoints directly above and below one another; however, no such symmetry is possible in **1**. While these structures appear qualitatively reasonable, it is well known¹¹ that accurate treatment of such long-range interactions requires substantially larger basis sets including more diffuse and higher angular momentum basis functions.

The structures found above were therefore re-optimised with the larger 6–311+G(d) and 6–311+G(2df) basis sets^{12,13} to provide more accurate energies and geometries, this time enforcing C_{2v} symmetry for **2** and retaining C_1 symmetry for **1** (MP2/6–311+G(2df) optimised structures are shown in Fig. 2). The importance of the basis set is demonstrated by the fact that the intermolecular distance falls by between 0.1 and 0.2 Å in these re-optimised structures (Table 1), although the overall face–face structural motif is unchanged. It is also evident that acrolein gets rather closer to benzene than does ethene, with ring centroid \cdots C=C midpoint distances of 3.22 Å and 3.30 Å, respectively. Changes in all other geometrical parameters between the isolated molecules and complexes **1** and **2** are negligible, the largest being just 0.003 Å in the C–C single bond and 0.4° in the C–C=O angle of acrolein in **1**. While the C_{2v} symmetry enforces co-parallel, aligned monomers in **2**, no such restrictions are placed on **1**. Nevertheless, the optimised geometry of **1** closely retains these patterns, with an angle of less than 3° between the mean planes of benzene and acrolein, and the midpoint of the C=C bond aligned almost directly over the centroid of the benzene ring (Fig. 2a).

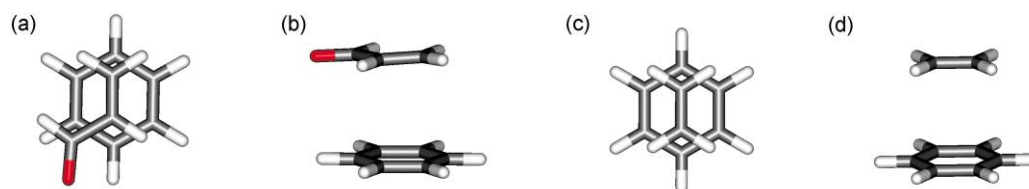
Interaction energies between benzene and ethene/acrolein are also reported in Table 1 for a variety of basis sets and theoretical methods, where again it is evident that the MP2/6–31G(d) is inadequate for the current problem. With larger basis sets,

† Electronic supplementary information (ESI) available: MP2/6–311+G(2df) optimised coordinates of complexes **1** and **2**. See <http://www.rsc.org/suppdata/ob/b210497k/>

Table 1 MP2 interaction energies and geometries of **1** and **2** (kJ mol⁻¹ and Å)

	1		2	
	Energy ^a	$r(\text{Ct} \cdots \text{Ct})^b$	Energy ^a	$r(\text{Ct} \cdots \text{Ct})^b$
MP2/6-31G(d)	16.33	3.334	10.59	3.507
MP2/6-311+G(d)	27.33	3.226	14.00	3.354
MP2/6-311+G(2df)	26.67 (17.09)	3.225	11.49 (5.76)	3.295
MP2/cc-pVTZ ^c	22.29 (16.33)	—	10.26 (6.03)	—
LMP2/cc-pVTZ ^c	18.29 ^e	—	4.30	—
LMP2/aug-cc-pVTZ ^c	20.14 ^e	—	8.27	—
LMP2/cc-pVQZ ^c	17.48 ^e	—	4.78	—
CCSD(T)/6-311G(d)	13.74	—	5.44	—
MP2/6-311G(d)	20.39	—	7.83	—
Δ CCSD	6.65	—	2.39	—
CCSD(T) ^{c,d}	9.68	—	3.64	—

^a Values in parentheses are counterpoise corrected. ^b Defined as the distance from the centroid of the benzene ring to the midpoint of the C=C bond. ^c Calculated at the MP2/6-311+G(2df) optimised geometry. ^d Corrected using the difference between MP2 & CCSD(T) interaction energies using the 6-311G(d) basis. ^e No counterpoise correction required for local MP2 energies.

**Fig. 2** a) 'Top' view of complex **1**; b) 'Side' view of complex **1**; c) 'Top' view of complex **2**; d) 'Side' view of complex **2**.

stabilisation energy is reasonably constant in the region of 16–17 kJ mol⁻¹ for **1** and 5–6 kJ mol⁻¹ for **2**, after correction for basis set superposition error (BSSE) by the counterpoise method of Boys and Bernardi.¹⁴ Tsuzuki *et al.*² demonstrated that this basis set is close to the saturation limit for complexes such as this, with stabilisation energies changing by less than 0.05 kJ mol⁻¹ when larger basis sets (*e.g.* cc-pVQZ) were used.

These calculations are at the limit of the available computational resources using standard MP2 calculations with Gaussian 98. However, the local MP2 method, as implemented in the MOLPRO¹⁵ suite of programs, allowed us to check the conclusion that larger basis sets should make little difference to the stabilisation energy. Similar methods have been used with some success for dimers of naphthalene and indole (albeit with rather smaller basis sets than used here).¹⁶ Table 1 demonstrates that this is indeed the case: results for the cc-pVTZ basis set confirm that this method gives similar stabilisation energies to the full MP2 method, while the larger aug-cc-pVTZ (which includes diffuse functions) and cc-pVQZ (which includes *g*-functions) show only slight changes in stabilisation. An added advantage of local correlation methods is that they are inherently BSSE free, since orbitals are localised onto each molecular fragment.¹⁷ These energies are therefore directly comparable to the counterpoise-corrected values, and show remarkable consistency across basis sets.

Following the procedure set out in Ref. 2, the likely result of more accurate calculation was estimated by comparing MP2 and CCSD(T) energies using the medium-sized 6-311G(d) basis set (this difference is relatively basis set independent). We calculate that the stabilisation energy in **1** is reduced by around 6.5 kJ mol⁻¹ at this more accurate method (the analogous value for the benzene dimer is 7.5 kJ mol⁻¹), while in complex **2** this correction is much lower at just 2.4 kJ mol⁻¹. Thus, we can estimate that the true stabilisation energy of complex **1** is 9.7 kJ mol⁻¹ (2.32 kcal mol⁻¹), which is remarkably similar to the 10.4 kJ mol⁻¹ quoted by Tsuzuki *et al.* for the most stable 'slipped-parallel' orientation of the benzene dimer at the same level of theory. The same methodology predicts that the stabilisation of **2** is just 3.6 kJ mol⁻¹ (0.87 kcal mol⁻¹).

Unlike the relatively homopolar benzene \cdots benzene and

benzene \cdots ethene complexes, the large stabilisation energy in complex **1** could be due to polar or charge transfer effects. We have checked the latter possibility by calculating NBO charges¹⁸ at the MP2/6-311+G(2df) level, which reveal that just 0.01 electrons are transferred from benzene to acrolein on complex formation. Thus, we can rule out charge transfer as a stabilisation mechanism for **1**, which instead appears to gain stability from the electrostatic attraction of the benzene π -system for the electron deficient double bond in acrolein. Further evidence for the nature of the $\pi \cdots \pi$ interaction comes from the local MP2 calculations, which allows for the breakdown of intermolecular correlation energy into dispersive, exchange, and ionic electrostatic contributions.¹⁷ In both complexes, LMP2/aug-cc-pVTZ calculations show that stabilisation is dominated by dispersion interactions, which account for around two-thirds of the total, with a smaller contribution from ionic interactions and a slight destabilisation from exchange effects.

In conclusion, we have used high-level theoretical calculations on model systems to demonstrate that $\pi \cdots \pi$ -interactions between aromatic and non-aromatic systems give rise to surprisingly stable complexes. To the best of our knowledge, this is the first time that such stability has been demonstrated for purely $\pi \cdots \pi$ -interactions, as opposed to charge transfer. Furthermore, in the case of relatively electron deficient α,β -unsaturated carbonyls these complexes have similar geometry (approximately 3 Å between π -systems) and stabilisation energy (around 10 kJ mol⁻¹) as found in the well-known benzene dimer. Thus, complexes such as **1** involving α,β -unsaturated carbonyls are remarkably stable, a result that we hope to exploit in Lewis acid catalysed enantioselective reactions of prochiral enones. Furthermore, the recognition that $\pi \cdots \pi$ stabilisation applies to non-aromatic species should be of more general importance, for instance in the fields of molecular recognition and crystal engineering.

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